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Welding Procedure Qualification and In-Service Weld Integrity Assessment Using Innovative Nondestructive SSM Technology

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Abstract

Regulations for the qualification of new welding procedures require the welding of metallic samples and the subsequent fabrication and testing of mechanical test specimens. These qualification methods are time consuming and expensive. Moreover, when cracks are generated due to service conditions (e.g., corrosion of oil and gas steel pipelines, fatigue damage, mechanical damage, etc.), some sections might have to be extracted from welded structures in order to fabricate tensile and fracture toughness specimens for structural integrity assessment. Again, the in-service weld evaluation process is cost-prohibitive and interrupts the performance of in-service structural components.

A patented *in-situ* Stress-Strain Microprobe^{TM} (SSM) system utilizes an Automated Ball Indentation (ABI) test technique to accurately determine the tensile and fracture toughness properties of metallic samples and structures in a nondestructive and localized fashion. The SSM technology now offers an alternative method to accomplish both weld procedure qualification and in-service weld assessment in a cost-effective, nondestructive, and speedy fashion. Furthermore, the ABI technique of the SSM system allows localized and complete evaluation of the welds and their heat-affected-zones (HAZs). This paper describes several SSM/ABI applications on nuclear pressure vessel steel welds and steel pipelines.

Introduction and Background

Many structural components such as pipelines and pressure vessels contain various circumferential (girth) and axial (seam) welds. The weld mechanical properties of new and in-service metallic structures must be appropriate for their maximum loading conditions. Thousands of miles of gas and oil transmission pipelines currently in operation in the USA and other countries have no documentation of their mechanical properties. Section 49 of the US Code of Federal Regulations (CFR) part 192.107 (b) (2) stipulates that for the pipe which is not tensile tested, a yield strength of 165 MPa (24,000 psi) must be used in the equation that determines the design pressure of the pipe section. The Automated Ball Indentation (ABI) test is an ***in-situ*** nondestructive technique that measures several key mechanical properties of metallic materials. Furthermore, ABI tests provide the actual yield strength values of base metal, welds, and heat-affected-zones which, most of the time, are higher than the conservative CFR value of 165 MPa; thus natural gas or oil pipeline up-rating (increasing transmission throughput) can be accomplished safely. Hence, ABI testing of pipelines is a better alternative to the destructive and expensive mechanical tests. Moreover, when cracks and other pipeline flaws are produced due to service conditions (e.g. corrosion and/or mechanical damage), the ABI-measured fracture toughness values can be used in the deterministic structural integrity assessment of the pipeline based on fracture mechanics analysis. The ABI test technique is described in detail in many publications [1-8]. Examples of using ABI test results in fitness-for-service analysis are described later. These include in-situ tests on a pipeline section without documentation for its grade and tensile properties, and testing small pieces from a catastrophic natural gas pipeline accident.

The SSM System and Its Nondestructive ABI Technique

The laboratory version of the patented [1] Stress-Strain Microprobe^{TM} (SSM) system (Fig. 1) has been in commercial use since 1991 on three continents, and the portable SSM version received a 1996 R&D 100 Award (considered by many researchers as the Nobel Prize of Applied Technology). Furthermore, in 1999, Advanced Technology Corporation (ATC) introduced a new miniature SSM system to provide even greater portability and easier field applicability (Fig. 2). Equipped with a small, portable battery pack and magnetic mounts, this system has proven to be a valuable test instrument for the pipeline industry. The accuracy, reliability, and easy field applicability of the SSM system to test pipeline materials with unknown properties have been demonstrated on samples and on pipeline sections from several major natural gas operators [6]. Fig. 3 shows examples of the ABI test data and stress-strain curve results (with comparison to the curve from the destructive tensile test). With a $600,000 grant from the US Department of Energy, ATC conducted numerous ABI-measured fracture toughness tests on several pressure vessel steel materials and welds and compared these with the results from destructive tests. The final report [7] is available for downloading from ATC's website: www.atc-ssm.com. Fig. 4 shows an example of the ABI-measured fracture toughness values and their comparison with those from destructive tests on a pressure vessel steel weld. Numerous industry and government users have requested a standard, and as a result, a draft ASTM Standard for the "ABI Test Methods" is currently in the balloting process under Committee E28 of ASTM International.

The ABI test is based on progressive indentation with intermediate partial unloadings until the desired maximum depth (maximum strain) is reached, and then the indenter is fully unloaded. The indentation load-depth data are collected continuously during the test using a 16-bit data acquisition system. The nonlinear, spherical geometry of the tungsten carbide indenter allows increasing strain as the indentation penetration depth is increased. Hence, the incremental values of load and plastic depth (associated with each partial unloading cycle) are converted to incremental values of true-stress and true-plastic-strain according to elasticity and plasticity theories [2,3]. The ABI test is fully automated (using a notebook computer, a data acquisition system, and a servo motor), and a single test is completed in less than two minutes. Furthermore, in addition to the ABI stress-strain curve measurements, the nondestructive and localized ABI technique of the SSM system provides fracture toughness properties that cannot be obtained from the destructive (and costly for operating pipelines) tensile test. The determination of fracture properties from ABI tests is described in detail elsewhere [7,8]. The initiation fracture toughness is calculated from the integration of the tri-axial deformation energy up to a critical depth (when the maximum pressure underneath the ball indenter equals the critical fracture stress of the steel material at the test temperature).

Fitness-for-Service Example No. 1

Documentation was missing for a 914-mm (36-in) diameter pipe in a refinery in Europe. This situation meant that the grade of the pipeline and its Specified Minimum Yield Strength (SMYS) were unknown. Instead of assuming a low/conservative value for the yield strength (as usually the case for low grades of steel pipelines such as Grade B or X42), field ABI tests were performed on the base metal, girth welds, and spiral welds of the pipe. The in-situ ABI-measured yield strength values of 300 MPa and up were higher than the previously assumed value for the base metal. Furthermore, there was no data available on both types of the pipeline welds. Since, the maximum pipeline pressure is a percentage of the yield strength, the operator was able to determine the safe operating pressure for this pipeline section based on the ABI-measured yield strength values of the base metal and the welds (girth and spiral).

Fig. 1 The laboratory version of the Stress-Strain Microprobe^{TM} (SSM) system is equipped with an environmental chamber for testing samples at low and high temperatures and a positioning table to allow accurate testing of specific weld areas and their heat-affected-zones.

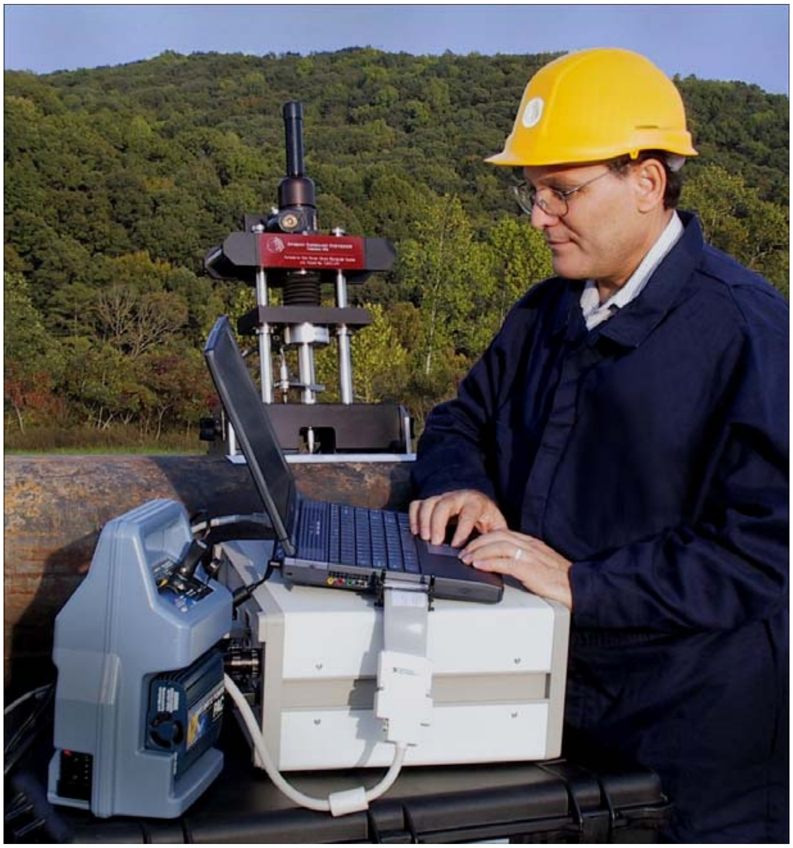

Fig. 2 The testing head of the miniature SSM system is mounted using electric magnets on a 356-mm (14-in) diameter steel pipeline.

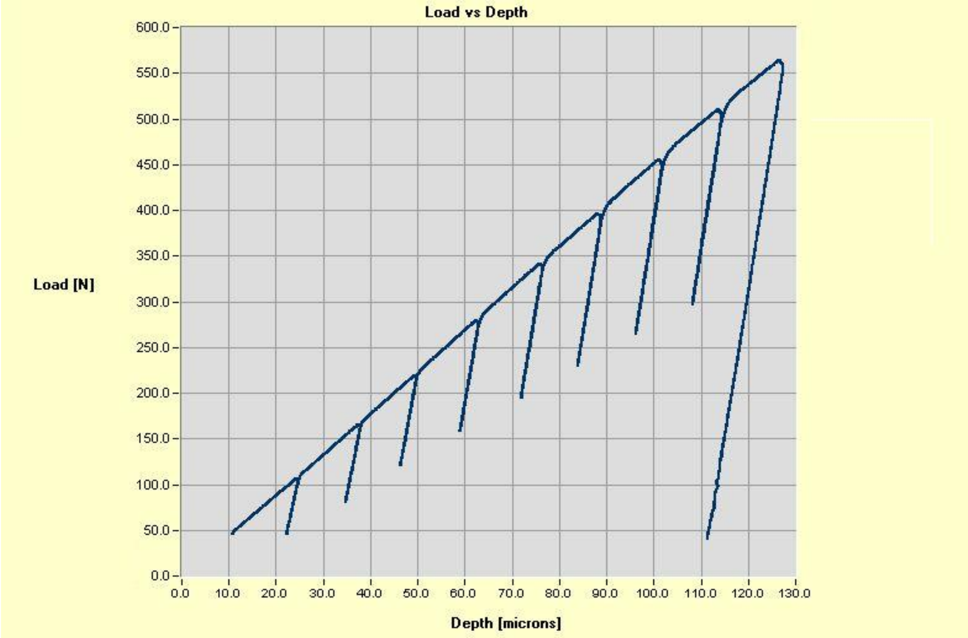

Fig. 3 (a) Load versus depth data from an ABI test on X52 pipeline steel using a 0.76-mm (0.030-in) diameter tungsten carbide indenter.

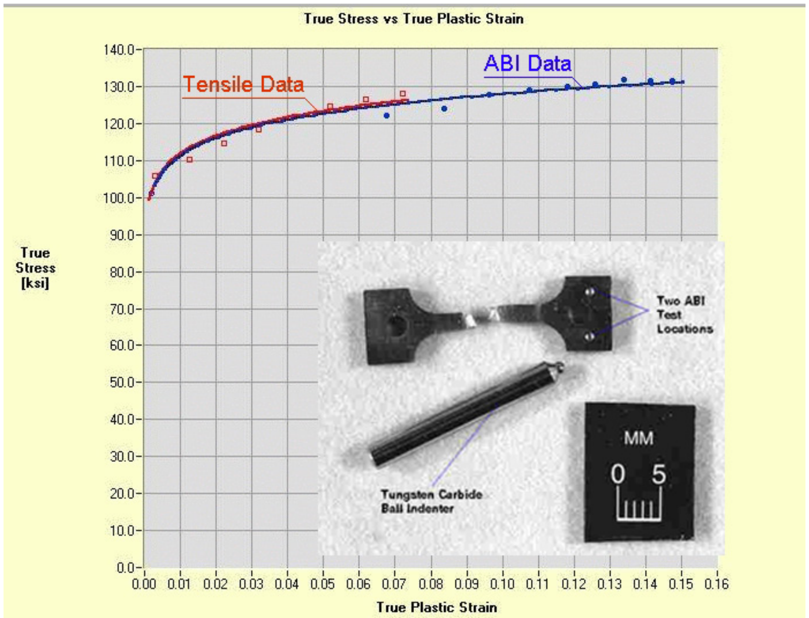

Fig. 3 (b) Comparison of true-stress versus true-plastic-strain curves from ABI and tensile tests on a high strength steel. (1 ksi = 6.895 MPa). The inset photo shows a tensile specimen and 1.57-mm (0.062-in) diameter tungsten carbide indenter.

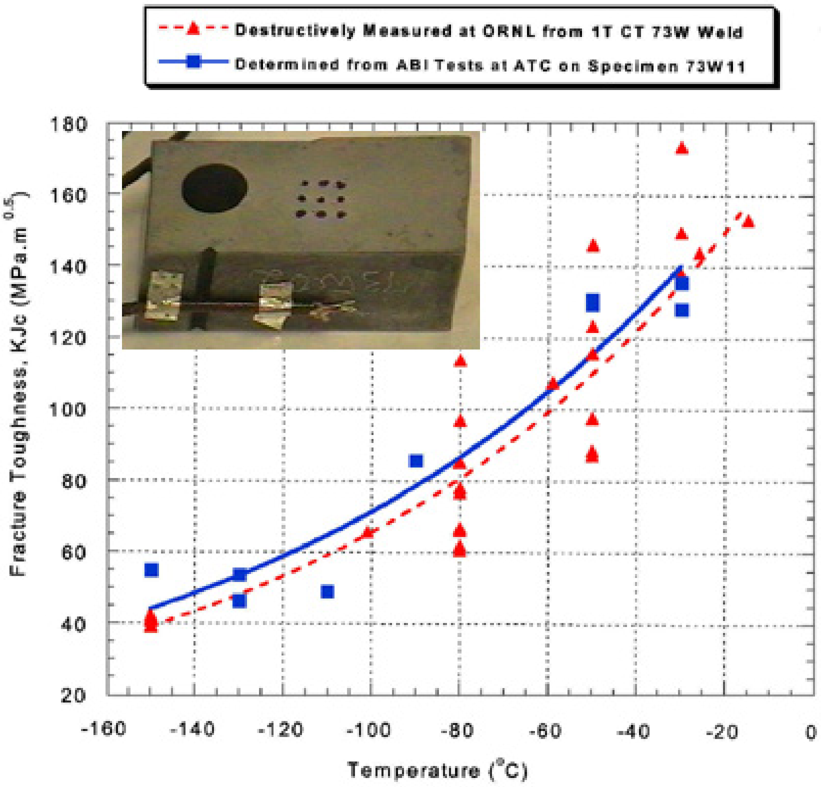

Fig. 4 Comparison between ABI-measured fracture toughness and destructive 1T CT fracture toughness test results of 73W weld of Oak Ridge National Laboratory (ORNL).

Fitness-for-Service Example No. 2

A catastrophic failure occurred in a natural gas plant on a cold winter night shortly following the leak of some liquid natural gas into a nearby natural gas line. The combination of cold temperature and high strain rate near a crack in the natural gas pipe resulted in the destruction of approximately a 12-meter section of a 508-mm (20-inch) diameter pipeline into several hundred small pieces. The plant operator was concerned that the pipeline steel might have poor tensile and fracture toughness properties since the fracture surfaces of many of the small pieces indicated brittle fracture. Furthermore, the plant operator was concerned about potential failures in three identical gas plants utilizing the same grade of pipeline steel. The remaining pieces from the exploded pipeline section were not sufficient to machine destructive tensile and fracture toughness specimens. Hence, the ABI technique was used to measure the tensile and fracture toughness properties from multiple tests on a few pipeline pieces. The ABI-measured tensile and fracture toughness results provided the basis for the fitness-for-service assessment of the remaining natural gas pipeline sections of the plant.

Although, the pipeline piece containing the crack was not found at the time of ATC's report, the ABI tests on several small pieces confirmed that the pipeline steel material met the mechanical properties specified for the seamless carbon steel pipe at the time of construction. Multiple ABI tests were conducted on a block machined from a small piece at several low temperatures. All ABI tests were conducted using a 0.51-mm (0.020-inch) diameter tungsten carbide indenter at a speed of 0.01 mm/s (0.0004 in/s), or a strain rate of 0.014/s, to a maximum indentation depth of 0.076 mm (0.003 in). Stress-strain curves and fracture toughness values were measured from the individual ABI tests. The reference temperature, T_o, defined in the ASTM Standard E1921-97 [Ref. 9, "Standard Test Method for Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range,"] as the test temperature corresponding to a median fracture toughness level of 100 MPa√m (90.9 ksi√in), was determined from the ABI tests at several low test temperatures. The ABI tests determined a T_o value of -24ºC for the base metal of the pipe. The ABI-determined fracture toughness median curve and its 95% and 5% confidence limit curves are shown in Fig. 5. The ABI-determined T_o value demonstrated that the pipeline material had a good static fracture toughness of 100 MPa√m at a low temperature of -24ºC that is lower than the normal pipeline operating temperatures in winter. However, these ABI-measured static fracture toughness values did not prevent brittle failure that resulted from the existence of a small crack (developed during pipeline service) and the combination of a very low temperature and dynamic loading at a high strain rate. The latter resulted from a valve leak and adiabatic expansion of liquid natural gas from a neighboring liquid line. It should be noted that all carbon steels have a low/brittle fracture toughness shelf with a median value of 30 MPa√m regardless of their much higher fracture toughness values at higher operating temperatures. Furthermore, dynamic fracture toughness values are lower than the static values at the same temperatures (i.e., the fracture toughness median curve is shifted to the right by an amount depending on the yield strength of the steel material). Since, the ABI-measured tensile and fracture toughness values of the small pieces proved that the pipeline material was adequate (fit-for-service), there was no need for in-situ testing of the remaining pipeline sections. The corrective action involved repairing the valves of the liquid line and replacing the exploded natural gas pipeline section.

Although the fracture toughness master curve is a new concept, many organizations are using it to assess the fitness-for-service of their steel structural components and their welds. Several publications are now available on the use of the master curve by the Welding Research Council, several US National Laboratories, and a few international nuclear and educational institutes. Also, the Pipeline Research Council International (PRCI) has a work-in-progress project on the applicability of the master curve to assess the integrity of girth welds. The major advantage of the master curve is the ability to test smaller size destructive specimens at a single temperature in order to obtain valid test results and a fracture toughness curve as a function of temperature in the transition region. The ABI-measured fracture toughness and its master curve is the only method that does not require destructive specimens (i.e., hot tapping is eliminated for operating pipelines), and it is nondestructive and localized (the latter feature is highly desirable for small welds and heat-affected-zones). Moreover, the ABI technique provides both tensile and fracture toughness properties from each single ABI test in a cost-effective and speedy manner.

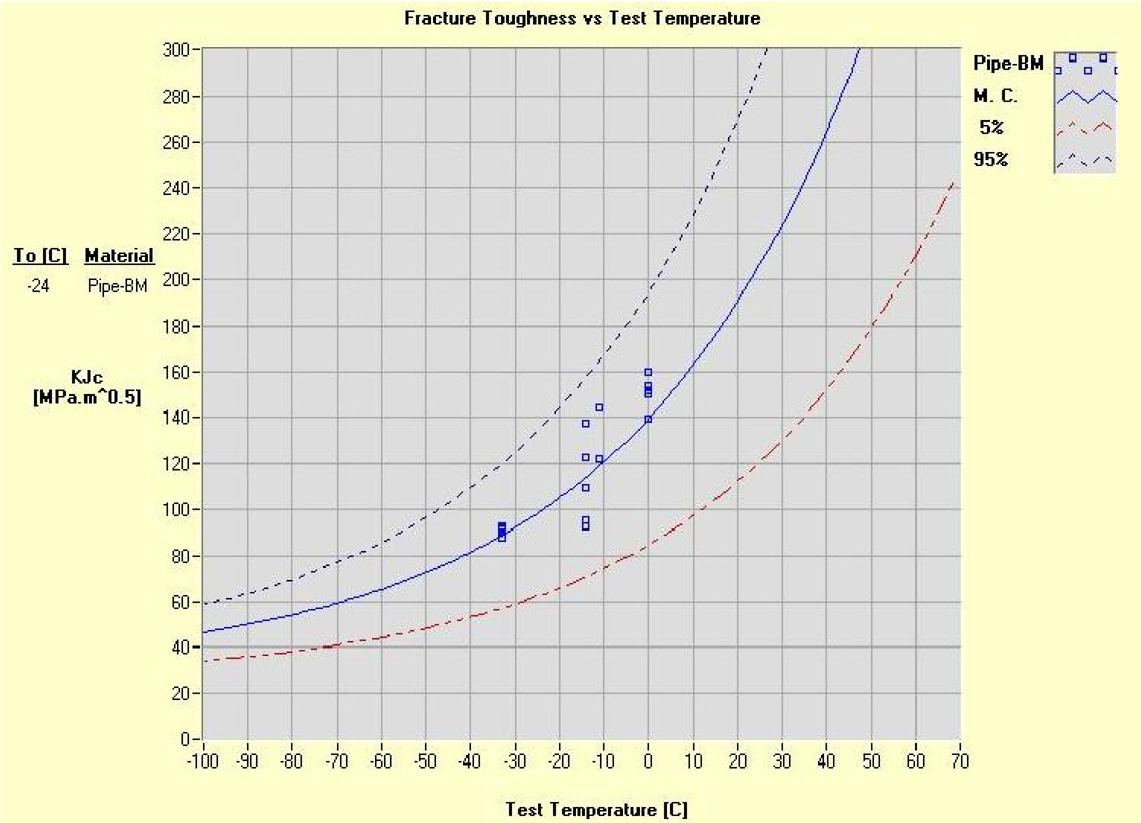

Fig. 5 Fracture toughness, K_{Jc}, values determined from 17 ABI tests conducted on a pipeline steel sample at four test temperatures.

Summary and Conclusions

The results presented briefly here and in detail in Refs. [6,7] demonstrate the capabilities of the Stress-Strain Microprobe^{TM} (SSM) system and its Automated Ball Indentation (ABI) test technique to nondestructively measure the tensile and fracture toughness properties of carbon steel materials in a reliable and accurate manner on samples and components. The use of the SSM system to test aged and new construction pipelines and their welds in the field will improve their structural integrity evaluation as well as their operational efficiency. For an accurate and complete fitness-for-service assessment, the following should be noted: (1) the use of the SMYS or the ABI-measured yield strength to calculate the maximum pipeline operating pressure is appropriate only when there are no cracks, and (2) when cracks exist (due to corrosion and/or mechanical damage), the ABI-measured fracture toughness values of the base metal and welds should be used to calculate the critical crack size. Calculating the critical crack size for a given pipeline geometry and pressure, based on deterministic fracture mechanics analysis, allows accurate decisions to be made regarding the repair or replacement and the frequency of crack/flaw inspections.

Although not presented in this paper, ABI tests were conducted successfully to determine flow and fracture toughness properties of welds in aluminum components, pipeline girth and Electric Resistance Welds (ERWs), and spot welds of aluminum and steel materials. The ABI technique is also applicable to evaluate the mechanical properties of the different zones of Friction Stir Welding (FSW). The nondestructive and localized nature of the ABI test technique allows its use for both weld qualifications as well as for assessing and monitoring the key mechanical properties of welds and their HAZs of in-service metallic structures.

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